Eur. Phys. J. C 46, 429–432 (2006)
Digital Object Identifier (DOI) 10.1140/epjc/s2006-02503-1

THE EUROPEAN
PHYSICAL JOURNAL C

High energy Cherenkov gluons at RHIC and LHC

In memory of E.L. Feinberg

I.M. Dremin[1,a], L.I. Sarycheva[2,b], K.Yu. Teplov[2,c]

[1] Lebedev Physical Institute, Moscow, Russia
[2] D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia

Received: 12 October 2005 / Revised version: 28 December 2005 /

Abstract. The collective effect of emission by the forward moving partons of high energy Cherenkov gluons in nucleus-nucleus collisions at RHIC and LHC energies is considered. It can reveal itself as peaks in the pseudorapidity distribution of jets at midrapidities, or as a ring-like structure of individual events in event-by-event analysis. The pseudorapidity distribution of centers of dense isolated groups of particles in the HIJING model is determined. It can be considered as the background for Cherenkov gluons. If peaks above this background are found in experiments, they indicate new collective effects.

The search for collective effects in hadronic and nuclear high-energy reactions has always been one of the mainstreams of experimental and theoretical investigations. Among them, Cherenkov gluons [1, 2] and Mach waves [3] were discussed long ago. Cherenkov gluons are the intuitive analogue to Cherenkov photons if the electron beam is replaced by the bunch of partons (quarks and gluons) traversing the nuclear medium. In turn, Mach waves can appear in this medium if the parton (jet) speed exceeds the speed of sound. Recently, the interest in these effects was revived [4–9] in connection with RHIC data [10] as reviewed in [4]. The common feature of these collective coherent processes is the particle production concentrated on a cone with the polar angle θ defined by the condition

$$\cos\theta = \frac{c_w}{v}\,, \tag{1}$$

if the infinite medium at rest is considered and the direction of the parton motion is chosen as the cone axis. Here v is the velocity of the parton producing these effects, c_w is the phase velocity of the gluons, or the sound velocity in the medium.

The main experimental signature of both effects would be two peaks in the pseudorapidity distribution of particles produced in high energy nuclear collisions, which are positioned in accordance with (1). The most visual image of these effects is the ring-like structure of events in the plane perpendicular to the direction of propagation of the body initiating them.

At high energies of initial partons (jets) $v \approx c$. The velocity c_w can range from quite low values to a value slightly below c according to present estimates for both effects (see [4]). The lowest values of c_w are obtained for rarefied media and low energy gluons, while larger c_w correspond to strong shock waves and high energy gluons.

For gluons, $c_w = c/n$, where n is their nuclear index of refraction in a nuclear matter through which they move. The necessary condition for this effect is that the real part of the index of refraction be larger than 1. This index was estimated from experimental data on hadronic reactions [2, 4] with the assumption that gluons as carriers of strong forces should possess the features common to hadronic reactions. Its value is proportional to the real part of the forward scattering amplitude, and we know from experiments (and from the theoretical description of its Breit–Wigner resonance shape and dispersion relations) that for any hadronic process it becomes positive in the presence of any resonance and at very high energies. Thus, the necessary condition is satisfied in these cases and one can expect observable effects with low energy and high energy gluons.

For low energy gluons that can generate hadronic resonances, the real part of the nuclear index of refraction can be written [4] as

$$\mathrm{Re}\, n^r = 1 + \Delta n^r_R = 1 + \frac{3m_\pi^3}{2\omega_r^2 \Gamma}\,. \tag{2}$$

Here ω_r is the energy required to produce a resonance. It can be of the order of the pion mass m_π. Since the widths of known resonances Γ are of the order of one hundred MeV, Δn^r_R can be of the order of 1. Therefore, according to (1), the angle of the particle emission is rather large in

---

[a] e-mail: dremin@lpi.ru
[b] e-mail: lis@alex.sinp.msu.ru
[c] e-mail: teplov@lav01.sinp.msu.ru

the target rest system. The effect can be observed at RHIC and LHC, if initial partons (jets) move at a large angle with respect to the collision axis. In such a way one can try to interpret the effect recently observed at RHIC [10] with two peaks in angular distribution about the direction of propagation of the companion jet created in the direction perpendicular to the collision axis. The peak position showed that $c_w = 0.33c$. Thus, it could be the emission of low energy Cherenkov gluons with nuclear index of refraction equal to three. In this case, the resonance production should be enlarged in this angular region. It can result in a different ratio of pions to protons compared to that outside this region. In [7] it was interpreted as Mach waves with $c_w = 0.33c$. However, a special trigger is needed to observe this effect as was done in [10]. Moreover, the production of the trigger and companion jets at 90° is a rather rare process, which requires high statistics experiments. This effect is unobservable at RHIC and LHC for the forward moving partons, because in this case, the large emission angles in the target rest system are trasformed to angles extremely close to π in RHIC and LHC systems. However, it could be observable for forward moving partons in fixed target experiments as peaks at about 70° but, strangely enough, no such observations have yet been presented.

The impinging nuclei can be considered as bunches of the forward/backward moving high energy partons passing through each other. Besides being unobservable at RHIC and LHC (as explained above) low energy gluons, each initial forward moving parton can emit high energy Cherenkov gluons when traversing the target nucleus (moreover, target partons can do the same in the opposite hemisphere). The real part of the nuclear index of refraction has been estimated [2] using the formula

$$\mathrm{Re}\, n^h(\omega) = 1 + \Delta n^h_R(\omega) = 1 + \frac{3m_\pi^3}{8\pi\omega}\sigma(\omega)\varrho(\omega)\,, \qquad (3)$$

where $\varrho(\omega) = \mathrm{Re}\, F/\,\mathrm{Im}\, F$, $F(\omega)$ and $\sigma(\omega)$ are the hadronic forward scattering amplitude and the cross section. It becomes positive above some threshold, increases and then decreases at high energies ω, so that

$$\Delta n^h_R(\omega) \approx \frac{a}{\omega}\,, \qquad (4)$$

where $a \approx 2 \times 10^{-3}$ GeV if $\varrho \approx 0.1$ as follows from experiments, and it is assumed to remain constant at higher energies. The index h refers to high energy gluons. Therefore, according to (1), the angle of the particle emission is quite small in the target rest system, but much larger than bremsstrahlung angles. If transformed to RHIC or LHC systems, these angles can become large (somewhere in the midrapidity region). This effect can be observed if initial partons (jets) move (almost) along the collision axis. There are numerous experimental indications in favor of this effect (see the review in [4]). The first one was presented in [11]. Most results are, however, either for individual cosmic rays or for special samples of events at accelerator energies.

Here we should mention that the finite length of nuclear targets can change somewhat the estimate (1): enlarge the transverse momenta of particles in Cherenkov jets and influence the difference between processes with different colliding nuclei [2,4].

In what follows, we discuss high energy Cherenkov gluons at RHIC and LHC energies produced by forward moving partons. The important problem of the experimental search for this effect is the shape of the background due to "ordinary" processes. Its influence should be minimized. To this end, we propose to use the distinctive feature of the production of high energy Cherenkov gluons. Namely, such gluons should produce a jet of particles that can be distinguished as a high density isolated group of particles. Therefore, the distributions of groups (jets) of particles should be considered rather than inclusive particle distributions. By separating such groups from experimental data one would increase the relative contribution of jets produced by Cherenkov gluons. By such a selection we exclude weakly correlated particles. Statistical fluctuations and hard QCD-jets are still accounted for, but their relative probability is reduced and the pseudorapidity distribution must be rather smooth. Therefore, the role of the background in the distribution of the centers of such groups becomes lower compared to the overall pseudorapidity distribution.

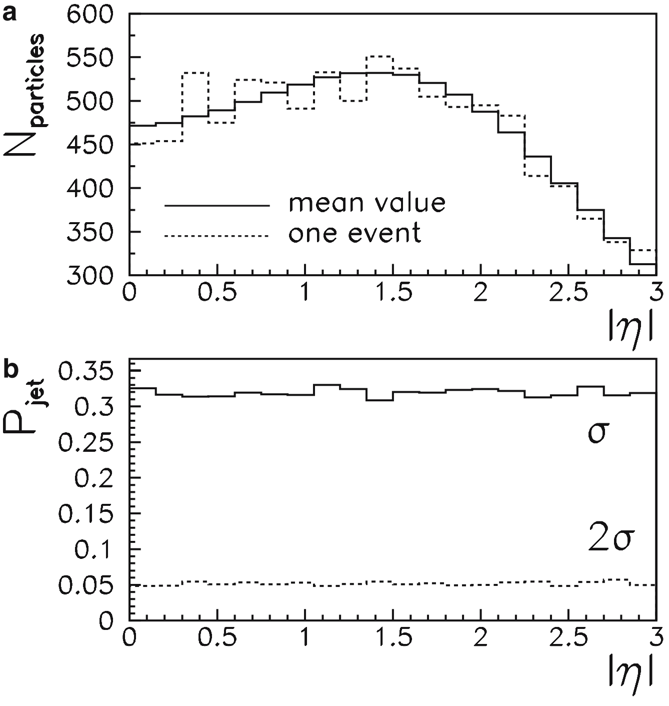

Fig. 1. **a** Pseudorapidity distribution in one HIJING event (*dashed histogram*) for central Au–Au collision at $\sqrt{s} =$ 200 A GeV is plotted over the inclusive HIJING distribution (*solid histogram*), $N_{\mathrm{particles}}$ – number of particles. Peaks above the inclusive plot are clearly seen. **b** Pseudorapidity distribution of the centers of dense isolated groups of particles similar to those shown in (**a**) and exceeding the inclusive plot by two and one standard deviations σ, P_{jet} – probability of finding a peak above mean + σ (2σ). This is the smooth background for further searches of collective effects

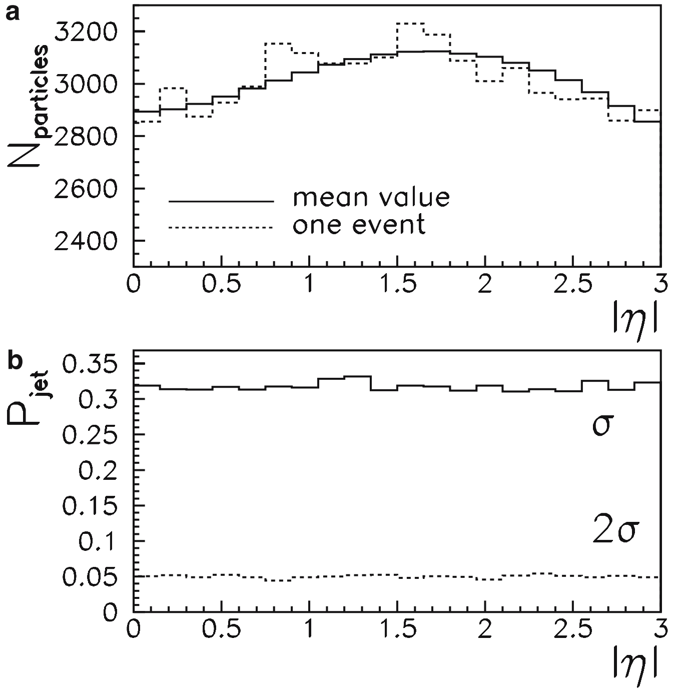

Fig. 2. a Pseudorapidity distribution in one HIJING event (*dashed histogram*) for central Pb–Pb collision at $\sqrt{s} =$ 5500 A GeV is plotted over the inclusive HIJING distribution (*solid histogram*), $N_{\text{particles}}$ — number of particles. Peaks above the inclusive plot are clearly seen. **b** Pseudorapidity distribution of the centers of dense isolated groups of particles similar to those shown in (**a**) and exceeding the inclusive plot by two and one standard deviations σ, P_{jet} – probability of finding a peak above mean + σ (2σ). This is the smooth background for further searches of collective effects

Peaks corresponding to Cherenkov gluons should be more pronounced.

To estimate the background we have used the HIJING model for central collisions ($b = 0$), for Au–Au collisions at RHIC energy $\sqrt{s} = 200$ A GeV and for Pb–Pb collisions at LHC energy $\sqrt{s} = 5500$ A GeV. 3500 events were generated in each case. We have chosen central collisions because the number of forward moving participants and, correspondingly, their role is larger in central collisions of heavy nuclei. Moreover, the Cherenkov radiation intensity is proportional to the length of the parton path in the medium. It is also larger in central collisions.

Then the peaks in individual HIJING events exceeding the regular distribution by more than one and two standard deviations have been separated. They can appear either as purely statistical fluctuations or as hard QCD-jets. Figures 1a and 2a show examples of such events (for RHIC and LHC energies, correspondingly) plotted over the smooth inclusive pseudorapidity distributions.

Peaks exceeding the distributions are clearly seen. All simulated events have been plotted and centers of peaks have been defined. Finally, the distribution of the centers of these peaks have been plotted. Figures 1b and 2b show these distributions for peaks exceeding the inclusive background at RHIC and LHC energies by two or one standard deviations. It is seen that these distributions are flat with extremely small irregularities. This agrees with our expectations that statistical fluctuations and QCD-jets do not have any preferred emission angle and should be randomly dispersed over the inclusive particle distribution. They can be considered as a background for the experimental search for Cherenkov gluons that have such preferred angle. High energy Cherenkov jets should have a quite narrow angular spread. If their angular width corresponds to a single bin in Figs. 1 and 2, then they would produce peaks twice exceeding this background even when their cross section is only five per cent of the cross section in the considered interval of pseudorapidities. If experimental data on group center distribution show some peaks at definite pseudorapidity values over this background, this can be indicative of a new collective effect, not considered in HIJING. These findings may be added to the experimental evidence in favor of such effects collected previously (they are reviewed in [4]).

It is easy to check from the figures that the levels of the background for 1σ and 2σ fluctuations correspond to the traditional statistical estimates of about 30% and 5%. However, in principle, these levels could be counted, e.g., from the inclusive pseudorapidity distribution, so the background would have a certain distinct shape. It should be stressed once again that the main result of this paper consists in the constancy of this background. The presence of the traditional QCD-jets in HIJING does not change the background. This simplifies experimental task of search for deviations from the flat distribution.

To conclude, the pseudorapidity distributions of the centers of dense isolated groups of particles (jets) exceeding the inclusive distribution in individual events are plotted for events generated according tothe HIJING model at RHIC and LHC energies. They are very flat and provide the background for further searches for collective effects such as Cherenkov gluons and Mach waves. If the peaks in the pseudorapidity plot of the centers of separated groups are found in experiments and fit the condition (1), then this will testify in favor of a Cherenkov gluons hypothesis. The positions of the peaks reveal such a property of hadronic matter as its nuclear index of refraction and can be valuable for understanding the equation of state of the nuclear medium.

Acknowledgements. This work was supported in part by the RFBR grants 03-02-16134, 04-02-16445-a, 04-02-16333, NSH-1936.2003.2. The authors are grateful to A. Demianov for useful discussions.

References

1. I.M. Dremin, Pis. Zh. Tekh. Fis. **30**, 152 (1979); JETP Lett. **30**, 140 (1979)
2. I.M. Dremin, Yad. Fiz. **33**, 1357 (1981); Sov. J. Nucl. Phys. **33**, 726 (1981)
3. A.E. Glassgold, W. Heckrotte, K.M. Watson, Ann. Phys. **6**, 1 (1959)
4. I.M. Dremin, hep-ph/0507167

5. A. Majumder, X.-N. Wang, nucl-th/0507062
6. V. Koch, A. Majumder, X.-N. Wang, nucl-th/0507063
7. J. Casalderrey-Solana, E.V. Shuryak, D. Teaney, hep-ph/0411315
8. H. Stöcker, Nucl. Phys. A **750**, 121 (2005)
9. J. Ruppert, B. Muller, Phys. Lett. B **618**, 123 (2005)
10. F. Wang (STAR), J. Phys. G **30**, 1299 (2004)
11. A.V. Apanasenko, N.A. Dobrotin, I.M. Dremin, K.A. Kotelnikov, Pisma v ZhETF **30**, 157 (1979); JETP Lett. **30**, 145 (1979)